FERMILAB Technical Division	**1.3 GHz Cryomodule (Type IV) Interconnect Bellows Assembly Engineering Note**	**Vessel No. ---** **Rev. No. --** **Date: 30 Mar 2011**

Fermilab Specification: 5500-ES-371043

Revision	***ER/ECO***	***Date***	**Description**	**Originated By**	**Approved By**
None	ER # ---	30-MAR-11	Original Issue	*R. Patel*	

Title: 1.3 GHz Cryomodule (Type IV) Interconnect Bellows Assembly Engineering Note

Author(s): Ronak Patel

Reviewer(s):

Drawing Numbers: D00000000756891

Materials: Stainless Steel (SA 240-316L)

Operating Temperature: 32° F to 100° F

External Operating Pressure: 14.7 psid

Internal Operating Pressure: 14.7 psig

Abstract Summary:
The bellows assembly used for connecting the 1.3 GHz Cryomodule to other Cryomodules is presented. The Interconnect Bellows Assembly has the length of 33.46 inches and a bellows outer diameter of 48.45 inches. This engineering note presents analysis and calculations for the bellows, shell, flanges and welds per Fermilab, ASME, and other applicable codes. The volumetric capacity of the vessel is 30.3 ft^3. This engineering note does not require a review as per FESHM 5033 because the volume is less than the 35 ft^3 requirement.

Applicable Codes:
ES&H Manual Chapter 5033, Fermilab.
"Boiler & Pressure Vessel Code" ASME VIII, Div.1, 2007 Edition

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1. Overall Data of the 1.3 GHz Interconnect Bellows Assembly

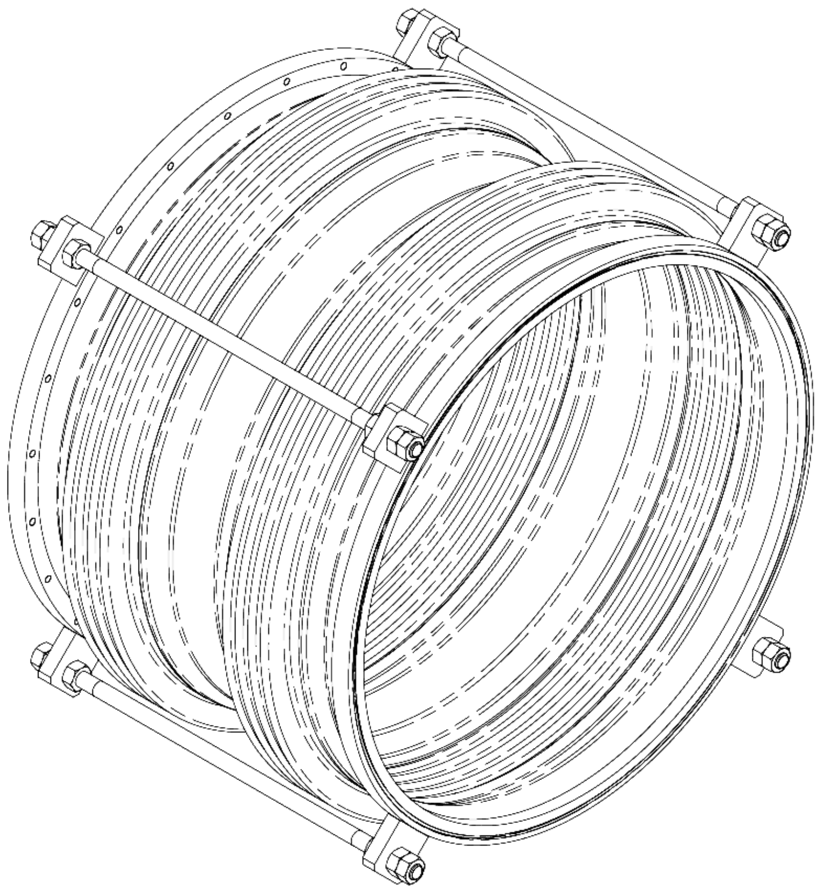
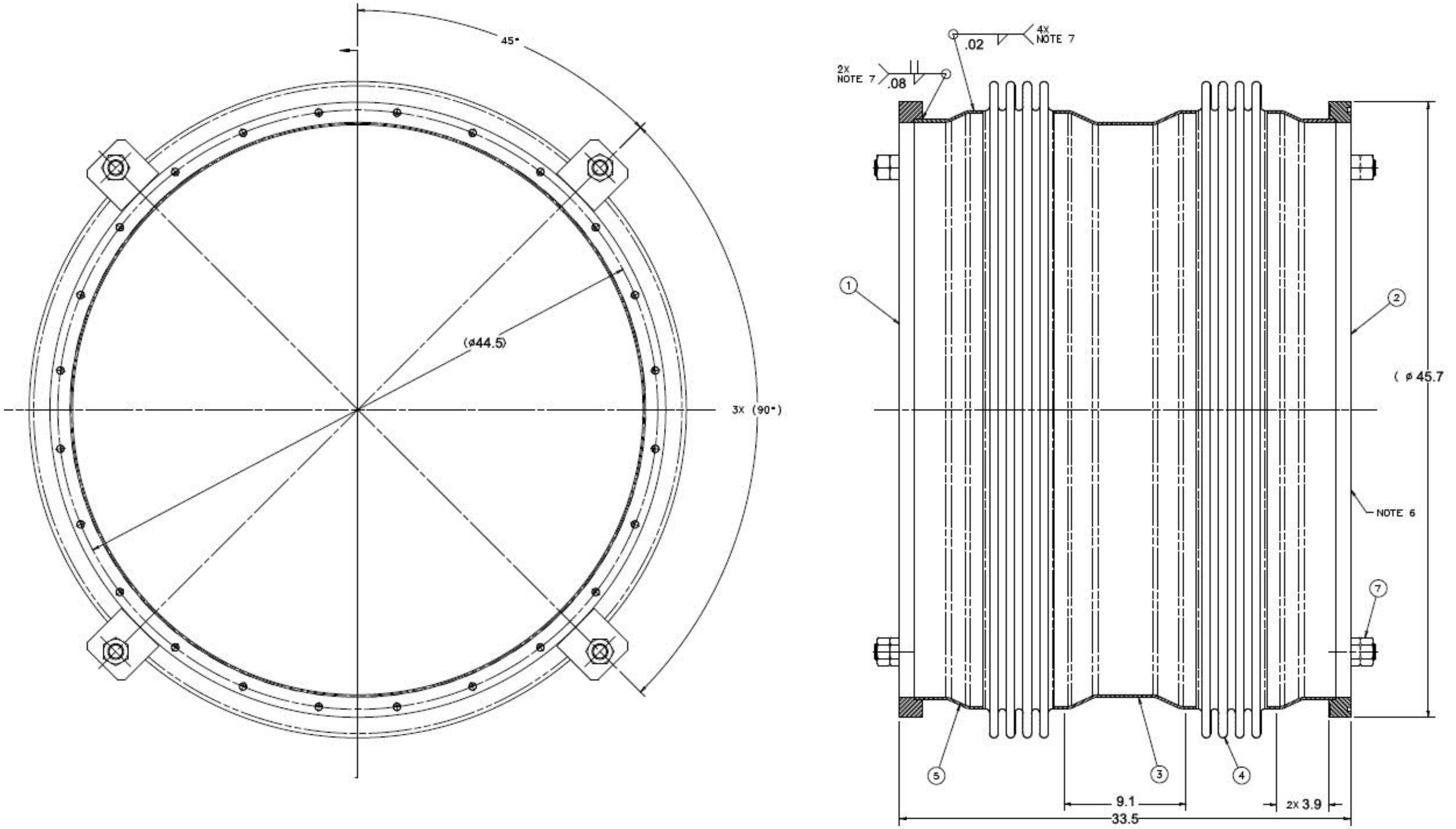


Figure 1. 1.3 GHz Interconnect Bellows Assembly

Design Parameters	
External design pressure	P_{ext} = 14.7 psi
Internal design pressure	P_{int} = 2 bar = 29 psi
Axial extension	(4.8 mm) = 0.188 *in*
Axial precompression	(4.8 mm) = 0.188 *in*
Lateral deflection	(4.8 mm) = 0.188 *in*
Minimum Fatigue Cycles	500



2.

Figure 2. Geometry Borders of 1.3 GHz Interconnect Bellows Reference drawing: D00000000756891

3. Bellows Analysis.

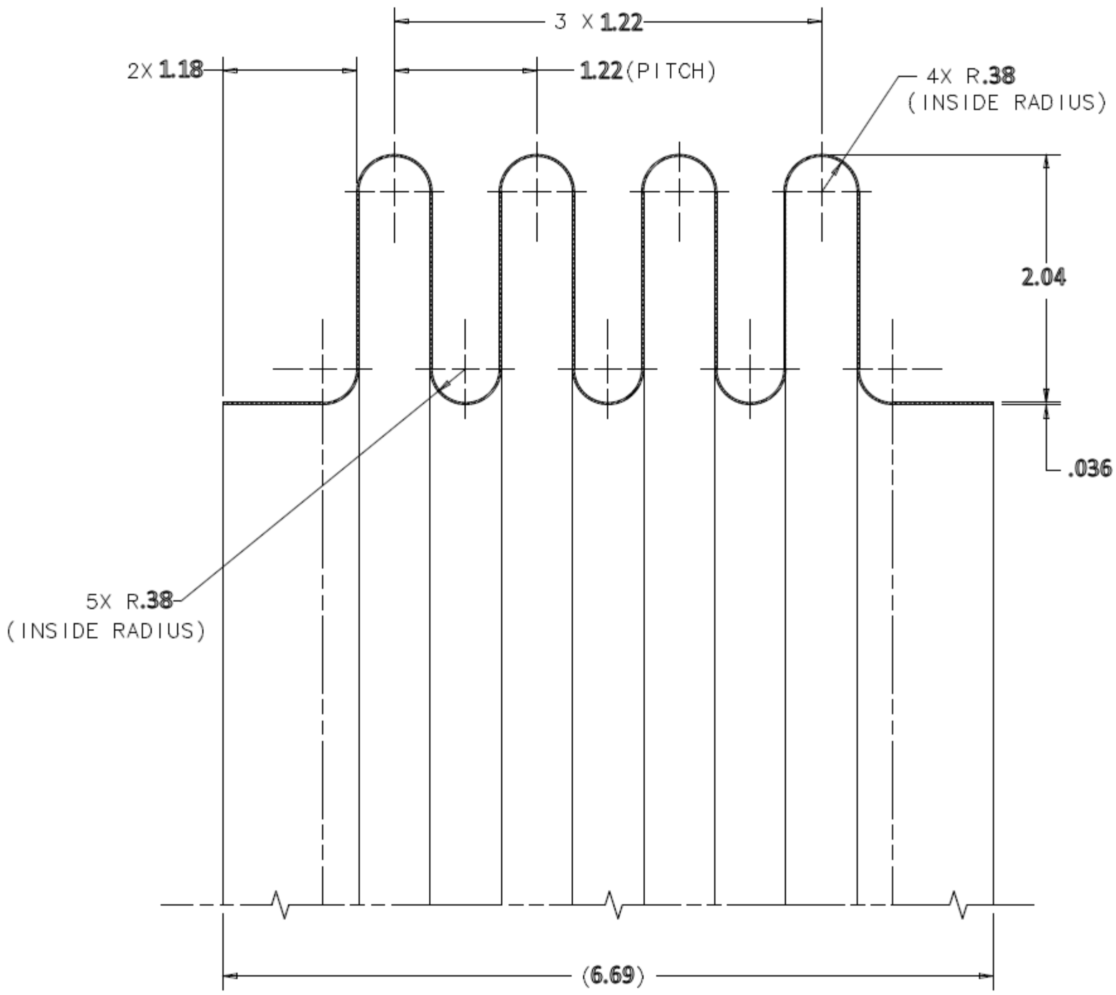


Figure 3. Basic dimensions of Bellows.
Reference drawing: D00000000756651, American Boa #1024130

Bellows Geometry		**Bellows Material Properties**	
Bellows Inside diameter	D_b = 44.38 in.	Material	Stainless Steel SA240-316L
Number of plies	n = 1	Module of Elasticity[1]	E_b= 2.83 x 10^7 psi = 195,000 MPa
Ply thickness	t_p = 0.036	Poisson's Ratio[2]	ν_b = 0.31
Convolution pitch:	q = 1.22 in.	Allowable Stress[3]	16,700 psi = 115.1 MPa
Number of convolutions:	N = 4	**Collar Geometry**	
Free length:	L_b = 4.88 in.	Collar Thickness	t_c = .187 in.
Depth of convolution:	W = 2.04 in.	Collar Length	L_c = .875 in
Bellows tangent length	L_T = 1.18 in.	Collar Material	Stainless Steel SA240-316L

[1] (Table TM 1, Section II, Part D, Customary, 2007)
[2] (Table 1A, Section II, Part D, Customary, 2007)
[3] (Table NF-1, Section II, Part D, Customary, 2007)

2.1 Bellows Instability Due to External Pressure (according 26-6.5.2 and UG-28)

The moment of inertia of one convolution cross section relative to the axis passing by the center of gravity and parallel to the axis of the bellow:

$$I_{xx} = nt_p\left[\frac{(2w-q)^3}{48} + 0.4q(w-2q)^2\right] =$$

$$= 1.0\times 0.0176in\times\left[\frac{(2\times 2.04in - 1.22in)^3}{48} + 0.4\times 1.22in(2.04in - 2\times 1.22in)^2\right] = 0.00995in^4$$

Where, t_p -thickness of the ply, corrected for thinning during forming:

$$t_p = t\sqrt{\frac{D_b}{D_m}} = 0.018in\sqrt{\frac{44.38in}{46.51in}} = 0.0176in$$

D_m - mean diameter of bellows convolutions:

$$D_m = D_b + w + nt = 44.38in + 2.04in + 1.0\times 0.018in = 46.51in$$

The thickness of the equivalent cylinder:

$$e_{eq} = \sqrt[3]{12(1-v_b^2)\frac{I_{xx}}{q}} = \sqrt[3]{12\times(1-0.31^2)\times\frac{0.00995in^4}{1.22in}} = 0.446in$$

The outside diameter of the equivalent cylinder:

$$D_{eq} = D_b + w + 2e_{eq} = 44.38in + 2.04in + 2\times 0.446in = 47.38in$$

The length of equivalent cylinder:

$$L_{eq} = Nq = 4\times 1.22in = 4.88in$$

The maximum allowable external pressure:

$$P_a = \frac{4\times \mathrm{B}}{3\frac{\mathrm{D_{eq}}}{\mathrm{e_{eq}}}};$$

When,

$$\frac{\mathrm{L_{eq}}}{\mathrm{D_{eq}}} = \frac{4.88in}{47.38in} = 0.103 \text{ and } \frac{\mathrm{D_{eq}}}{\mathrm{e_{eq}}} = \frac{47.56in}{0.4709in} = 106.3$$

From section UG-28, Figure G and Figure HA-4 in Subpart 3 of Section II, part D, ASME VIII, Div. 1 it is found out that

$$\mathrm{A} \approx 0.0225 \text{ and } \mathrm{B} \approx 15500$$

Then

$$P_a = \frac{4\times 15500}{3\times\frac{47.38in}{0.446in}} \approx 106\,psi$$

Result: since P_a is greater than the external design pressure P of 14.7*psi*, the bellow equivalent dimensions are satisfactory.

2.2 Bellows under Internal Pressure.

The bellows design under internal pressure needs to conform to the following requirements. The tangent and collar circumferential membrane stresses must fall below the allowable stress of 16,700 psi. In addition, the meridional membrane plus bending stresses must fall below 50,100 psi. For the bellows calculation, the Microsoft Excel program by Tom Page was used (See Excel spreadsheet in Appendix 6).

Result: the bellows design is satisfactory.

3. Connecting Rod Analysis

The four rods connecting the end flanges of the bellows are subjected to compressive loads while under vacuum. If the bellows assembly is flanged from both sides, the compressive force exerted on each rod with an internal pressure of zero and external pressure of 14.7 psi (atmospheric pressure) is:

$$\mathrm{F_R} = \frac{F_{Total1}}{4} = \frac{2\cdot(Area\cdot \mathrm{Pr}essure)}{4} = \frac{2\cdot(42.69/2)^2\cdot\pi)\cdot 14.7}{4} = 10{,}520 lb$$

If the bellows assembly is flanged on one end, and laid on the ground on the other end, the force exerted on each rod will be half of this, or 5260 lb.

It must first be determined whether the Euler formula or J.B. Johnson formula should be used to calculate the critical pressure, P_{CR}. This determination is made through the value of the quantity Q/k^2, where:

$$\mathrm{Q} = \frac{S_y \ell^2}{n\pi^2 E} \quad \text{and for a solid cylindrical rod,} \quad \mathrm{k} = \frac{r}{\sqrt{2}}$$

S_y= 16700 (allowable stress)
ℓ = 32.8 (rod length)
r =.537 (min threaded rod radius)
n= 2 (for rods with one end fixed and other end free but guided)
E= 2.83 x 10^7 (modulus of elasticity)

Through this calculation, Q = .0308, k = .379, and Q/k^2=.213 < 2. Therefore, the J.B. Johnson formula will be used:

$$\mathrm{P_{CR}} = AS_y\left(1-\frac{Q}{4k^2}\right) = 0.907\cdot 16700\left(1-\frac{.0308}{4(.379)^2}\right) = 14{,}300 lb$$

Result: During vacuum leak check, the bellows assembly will be oriented with one end on the ground and the other end flanged. With this orientation, each rod will see a force of 5260 lb. Even if both sides of the bellows are flanged, the critical pressure of 14,300 lb is greater than the force on the rod of 10,520 lb. Therefore, the connecting rod compressive strength is satisfactory for internal vacuum.

4. Weld analysis.

4.1 Ring to end Flange Welding (x2)

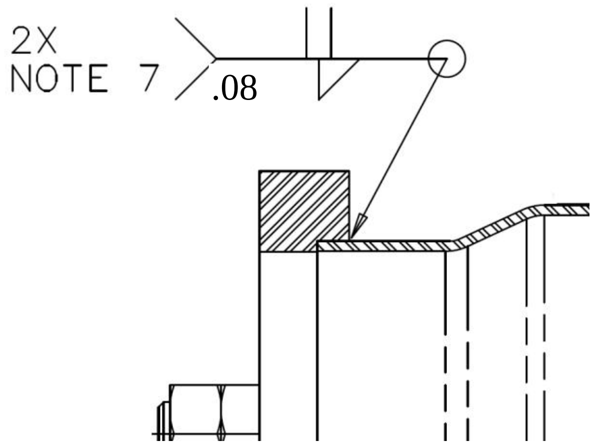


Figure 5 Weld Dimensions: Bellows-collars connection.
Reference drawings: D00000000756891

The sizes of the weld are satisfactory because it meets requirements of the Code, according to the rules in Mandatory Appendix 2, 2-4 Circular Flange Types, Fig.2-4, sketches 3.

4.2 Bellows to Ring Flange Welding (x4)

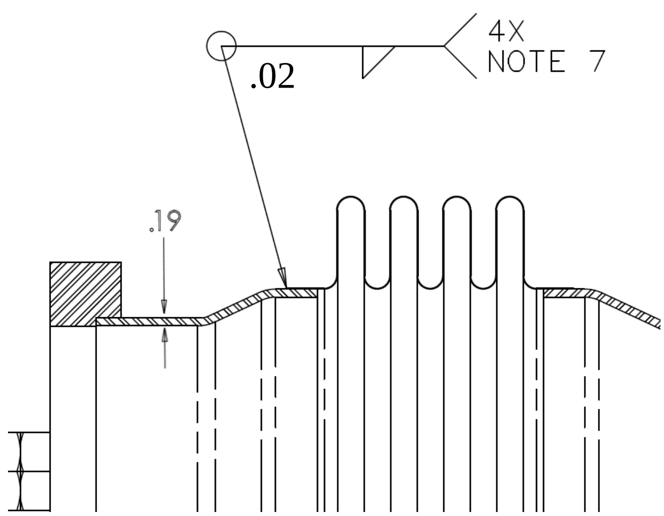


Figure 6 Weld Dimensions: Bellows-Ring Flanges connections.
Reference drawings: D00000000756891

The sizes of the weld are satisfactory because they meet requirements of the Code (Fig.UW-13.1, sketch “a”, 2007 SECTION VIII-DIVISION 1)

5. Conclusion:

The bellows conforms to the guidelines outlined in the ASME code. The part meets the criteria for stability due to both internal and external pressure. In addition, all of the welds are satisfactory and code approved.

6. Appendix.

1.3 GHz Bellows design calculation (by Tom Page Excel Spreadsheet)

Bellows Description:	1.3 GHz Interconnect Bellows						
Prepared By:	R. Patel using T. Page Spreadsheet						
Date:	3/15/2011						
Design Basis:	Expansion Joint Manufacturers Association Standard, 7th Edition, ERRATA 2002						
Allowable Stress Basis:	ASME Section II, Part D, 1998 Edition, 2000 Addenda						
Bellows Geometry				***Design Parameters***			
Bellows Inside Diameter, Db, (in.)		44.38		Design Pressure, P, (psi)			14.7
Number of Plies, n		1		Axial Extension, (in.)			0.188
Ply Thickness, t, (in.)		0.036		Axial Precompression, (in.)			0.188
Free length, Lb, (in.)		4.88		Lateral Deflection, y, (in.)			0.188
Number of Convolutions, N		4		Minimum Fatigue Cycles			500
Depth of Convolution, w, (in.)		2.040		***Collar Geometry***			
Bellows Tangent Length, Lt, (in.)		1.180		Collar Thickness, tc, (in.)			0.187
Bellows Material		316L		Collar Length, Lc, (in.)			0.875
Allowable Stress, Sab, (psi)		16,700		Collar Modulus of Elasticity, Ec, (psi)			2.83E+07
Modulus of Elasticity, Eb, (psi)		2.83E+07		Allowable Stress (304 SS), Sac, (psi)			16,700
Intermediate Calculations							
Convolution Pitch, q, (in.)		1.220		Stiffening Factor, k			0.6
Bellows Mean Diameter, Dm, (in.)		46.456		Material Constant, c			1.86E+06
Bellows Outside Diameter, (in.)		48.532		Material Constant, b			54,000
Collar Mean Diameter, Dc, (in.)		44.639		Manufacturing Constant, a			3.4
Total Axial Movement, (in.)		0.376		Factor from Figure C24, Cp			0.7789
Axial Movement Per Convolution, ex		0.0940		Factor from Figure C25, Cf			1.4406
Lateral Movement Per Convolution, ey		1.2925		Factor from Figure C26, Cd			1.4357
Bellows Mat. Thickness Factor, tp		0.0352		Material Strength Factor, Cm			3.0
Circumferential Stress Factor, Kr		1.607		Transition Point Factor, Cz			0.3863
X-Sect. Area for 1 Conv., Ac, (in.^2)		0.1681		Inplane Instability Stress Ratio, delta			2.5881
Yield Strength at Design Temp., Sy		50,250		Inplane Interaction Factor, alpha			27.3217
Bellows Stress Analysis					*Actual Stress*	*Allowable Stress*	
Tangent Circumferential Membrane Stress Due to Pressure, S1, (psi)					1,655	16,700	Pass
Collar Circumferential Membrane Stress Due to Pressure, S1', (psi)					1,672	16,700	Pass
Circumferential Membrane Stress Due to Internal Pressure, S2, (psi)					3,982	16,700	Pass
Meridional Membrane Stress Due to Internal Pressure, S3, (psi)					426	*N/A*	
Meridional Bending Stress Due to Internal Pressure, S4, (psi)					19,244	*N/A*	
Meridional Membrane + Bending Stress Due to Pressure, S3+S4, (psi)					19,670	50,100	Pass
Meridional Membrane Stress Due to Deflection, S5, (psi)					135	*N/A*	
Meridional Bending Stress Due to Deflection, S6, (psi)					26,110	*N/A*	
Maximum Design Pressure Based on Squirm, Psc, (psi)					107		
Maximum Design Pressure Based on Inplane Instability, Psi, (psi)					32		
Fatigue Characteristics						*Minimum*	
Total Stress Range for All Movements, St, (psi)					40,013	*N/A*	
Fatigue Life (cycles to failure), Nc					16,631,347	500	Pass
Spring Rates							
Theoretical Axial Elastic Spring Rate, (lbs./in.)					1,990		
							Rev. 3, 4/26/06